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STATUS OF μ DECAYS*

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Abstract

A short theoretical review of the weak interaction is presented with particular emphasis on the implications to normal and rare muon decay processes. This review addresses the standard theory, left-right symmetric theories, theories with horizontal symmetries, and composite models. A survey of experiments currently in progress to study both rare and normal muon decays is then presented with particular emphasis on the Los Alamos high statistics muon decay experiment and its implications for left-right symmetric theories.

I. INTRODUCTION

The muon has contributed greatly to our understanding of the nature of the weak interaction since its discovery in 1938 by Anderson and Neddermeyer. Early searches for decays like $\mu \rightarrow e\gamma$ and $\mu \rightarrow ee\bar{e}$ provided some of the evidence for the existence of what is now referred to as lepton flavor conservation. Furthermore, the measurement of the electron energy spectrum and angular distribution from ordinary muon decay, $\mu \rightarrow e\bar{\nu}_e\nu_\mu$, is one of the most fundamental in particle physics in that it is the best way to determine the constants of the weak interaction. These studies have led to limits on the V-A character of the theory. In recent years with the advent of the idea that the theories of nature are described by renormalizable gauge theories, the questions of lepton flavor violation and the exact nature of the weak interaction have taken on even greater importance. Consequently, experiments that search for possible rare decay modes of the muon and measurement of the normal decay mode to even greater precision have been mounted throughout the world. In this talk I will give a brief description of some of the modern theoretical ideas that have been put forward to help unify our understanding of particle physics and describe what muon decays have to say about these theories. I will, because of time constraints, limit this discussion to the standard theory of electroweak interactions (the Weinberg-Glashow-Salam theory), left-right symmetric theories, theories that have horizontal symmetries, and composite models. The majority of the talk will then be devoted to a description of various experiments that have been mounted to study muon decays--both rare decay mode searches and normal decay mode studies.

II. MODELS OF THE ELECTROWEAK INTERACTION

A. The Standard Theory

The spectrum of ordinary muon decay may be precisely calculated from the presently accepted "standard theory," the Weinberg-Glashow-Salam theory,[1] of electroweak interactions. In this theory, the neutrinos are two-component and massless and the only interactions that enter are vector and axial vector, of equal magnitude and opposite sign, V-A. The theory also has the characteristic that lepton flavor conservation is exact.

The V-A Lorentz structure of the weak interaction can be tested by precise measurements of the electron spectrum from ordinary muon decay. The spectrum is characterized (to first order in m_e/m_μ and integrated over the positron polarization) by[2]

$$\frac{dN}{x^2\, dx\, d(\cos\theta)} \propto (3-2x) + (\tfrac{4}{3}\rho-1)\,(4x-3) + 12\,\frac{m_e}{m_\mu}\,\frac{(1-x)}{x^2}\,\eta$$

$$+ \left[(2x-1) + (\tfrac{4}{3}\delta-1)\,(4x-3)\right] \xi \vec{P}_\mu \cos\theta$$

where m_e is the positron mass, θ is the angle of emission of the positron with respect to the muon polarization vector, $\vec{P}_\mu$, m_μ is the muon mass, and x is the reduced positron energy ($x = 2E/m_\mu$ where E is the positron energy). The Michel parameters ρ, η, ξ, and δ characterize the spectrum. The standard theory predicts[2]

$$\rho = \delta = \frac{3}{4},\ \xi = 1,\ \text{and}\ \eta = 0.$$

One can also measure the average longitudinal polarization of the positron, $\langle P_L \rangle = \xi'$, and the parameters α and β, as well as, α' and β' that characterize, respectively P_{T2} and P_{T2}, the two transverse components of the positron polarization. (See Fig. 1 for a definition of these polarization components.[3]) Table I gives the current world average values for these parameters. Derenzo[4] has used these data for ρ, η, ξ, and δ to place limits on the weak interaction coupling constants. The result of this analysis is shown in Table II. As can be seen from the table, the current limits on the Lorentz structure of the weak interaction allows up to 30% admixture of something other than a pure V-A structure. A more recent but somewhat more model-dependent analysis of the Lorentz structure has recently been carried out by Mursula, et al.,[5] and they have set the limits on the non-(V-A) structure at about 10%.

As stated earlier the standard model has as one of its characteristics the exact conservation of lepton flavor. However, a minimal extension of the standard model can be made by introducing neutral leptons N_μ and N_e that couple to the muon and electron weak currents and that are themselves Cabibbo-like mixtures of nondegenerate mass eigenstates N_1 and N_2,

$$N_\mu = N_1 \cos\theta + N_2 \sin\theta$$
$$N_e = -N_1 \sin\theta + N_2 \cos\theta.$$

In this case, $\mu \to e\gamma$ would be possible and its branching ratio, with respect to ordinary muon decay, would be approximately given by[6]

$$B(\mu \to e\gamma) \simeq \left(\frac{3\alpha}{32\pi}\right) \delta^2$$

$$\delta \simeq \sin\theta \cos\theta \frac{(M_1^2 - M_2^2)}{M_W^2}$$

where M_W is the mass of the charged intermediate vector boson, W. If the branching ratio is found to be $\simeq 10^{-12}$ (about the best attainable limit of currently planned experiments) and if θ is of the order of the Cabibbo angle, it would indicate that

$$M_1^2 - M_2^2 \sim 5\ \mathrm{GeV}^2$$

and this in turn would imply that there exist neutral leptons much heavier than the associated charged leptons. By turning the argument around, the current upper limit of

$$B\ (\mu \to e\gamma) < 1.7 \times 10^{-10} \qquad (90\%\ \text{confidence})$$

says that $\delta < 10^{-3}$. Along these lines, Shrock[7] has carried out a study to determine what can be learned about such neutrino mixing from rare muon decay processes as well as ordinary muon decays. He has shown that though these processes can set important limits, the best limits on neutrino mixing will come from K-decay studies.

B. Left-Right Symmetric Theories

One of the extensions of the standard theory of electroweak interactions is a theory of manifest left-right symmetry.[8,9] Here the mass eigenstates of the charged bosons, W_1 and W_2, are expressed in terms of the electroweak fields, W_L and W_R, as

$$W_1 = W_L \cos\zeta - W_R \sin\zeta$$
$$W_2 = W_L \sin\zeta + W_R \cos\zeta .$$

This extension is important from a theoretical standpoint for several reasons. Firstly, it restores parity conservation as a high-energy symmetry of weak interactions. It also says that the observed parity violation in weak processes is a low energy phenomenon of spontaneous symmetry breakdown wherein the mass of the right-handed boson is much larger than that of the left-handed boson. Riazuddin, Marshak, and Mohapatra[10] have also shown that though reasonable extensions of the standard theory can accommodate one Dirac or Majorana neutrino of arbitrary mass per lepton generation, a left-right symmetric theory predicts two Majorana neutrinos in each generation. Furthermore, a natural consequence of this symmetry is that one of the neutrinos will be light, ~ 1 eV, and predominately couple to the W_L, and the other neutrino will be more massive, > 100 GeV, and predominately coupled to the W_R. This type of neutrino structure would be indicated if neutrinos will light, ~ 1 eV, and predominately coupled to the W_L, and the other neutrino will be more massive, > 100 GeV, and predominately coupled to the W_R. This type of neutrino structure would be indicated if neutrino-less double beta decay were observed or if $\mu^- + A(Z) \rightarrow e^+ + A(Z-2)$ were observed.

From a phenomological view point, one is then interested in placing limits on the quantities ζ and $\kappa \equiv [M(W_1)/M(W_2)]^2$. The dominance of the left-handed current at presently accessible energies would be due to a large mass W_R but one such that the $W_L - W_R$ mass splitting is small on the grand unification scale. A purely left-handed effective interaction would have $\kappa = \zeta = 0$. This model has been studied by Beg[8] et al. and expanded by by Holstein and Treimon.[9] The best limits on these quantities come from a study of normal muon decay and nucleon β decay. Figure 2 shows the currently allowed limits on these quantities. Note that the most restrictive limit comes from the very recently published results of Mark Strovink's group[11] who measured the quantity $\xi P_\mu \delta/\rho > 0.9959$ to 90% confidence. Figure 2 shows that for $M(W_R) \rightarrow \infty$, $|\zeta| < 0.045$ and it shows that for any mixing angle, $M(W_R) > 380$ GeV. On the other hand, Beall, Bander, and Soni[12] have used a more model-dependent analysis of the $K_L - K_S$ mass difference to show that $M(W_R)$ must must be greater than about 1.6 TeV.

Before leaving this subject, I would like to point out that Oka[13] has demonstrated that data from the $\Delta S = 1$ semileptonic hyperon decays are inconsistent with the Cabibbo model. He then shows that the discrepancy may be accounted for in a left-right symmetric gauge theory and this discrepancy has been taken as a possible indication of right-handed currents.

C. Horizontal Gauge Theories

One of the shortcomings of the standard theory is that it does nothing to explain what has become known as the generation problem. That is to say, within the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ theory there is no obvious reason for the existence of the three families of quarks and leptons that are currently observed. One of the explanations put forward is that some weak "horizontal," i.e. between generations, force exists that requires the presence of several fermionic generations.[14] Such a force would have horizontal gauge bosons that have large masses compared to the those of the "vertical" gauge bosons, the W and the Z. From a qualitative point of view, these horizontal interactions would cause flavor mixing contributions to be present in normal muon decay. They would also contribute to lepton flavor violating processes like $\mu \to ee\bar{e}$ and $K \to \pi\nu\bar{e}$. Montvay[14] has done a study of the limits that muon-, tau-, and K-decay experiments have placed on such theories. He has shown that if the coupling strength is equal to the Weinberg-Glashow-Salam strength, then the mass of the gauge boson must be at least $10\, M_W \sim 1$ TeV, or the mixing angles must be unnaturally small. Consequently, though horizontal symmetries may only contribute to normal muon decay at the level of 10^{-4}, they may still be important in rare decay processes. Montvay then concludes that the most optimistic view favoring horizontal gauge symmetries is that the lack of positive evidence on horizontal weak interactions is due to the lightest horizontal gauge bosons acting mainly on the second and third generation fermions. Stronger limits on lepton flavor violating interactions could put further constraints on these theories.

D. Composite Theories

An attempt has also been made to try to explain the generation problem by saying that the various fermionic families are excited states of more fundamental spin-1/2 and spin-0 particles. In such theories, processes like $\mu \to e\gamma$ and $\mu \to e\gamma\gamma$ would be akin to one-photon and two-photon decays of the excited hydrogen atom. One is then faced with the questions of why the rate for such decays is so small and why the electron and muon have Dirac magnetic moments shown by the precision (g-2) measurements. The latter question has been answered by showing that the present (g-2) experiment is compatible with composite systems where the constituent particles have large masses ($> 10^7$ GeV). Tomozawa[15] has carried out an analysis of the rare decay modes $\mu \to e\gamma$ and $\mu \to e\gamma\gamma$ and shown that the current limits on these rare decays would be compatible with a lower bound on the constituent particle masses of $M > 10^9$ GeV. One is then forced to find a satisfactory method of explaining the smallness of the mass scale of the observed particle spectra arising from a much larger mass scale of a composite system.

III. MUON DECAY EXPERIMENTS

I will devote the rest of this talk to a discussion of the currently planned or recently completed experiments on muon decay. The first section will be a discussion of rare decay experiments followed by a discussion of normal decay experiments.

A. Rare Decay Experiments

Table III shows the current world upper limits for three rare decay modes and two lepton flavor violating muon conversion processes. As can be seen in the table, there is considerable interest at the world's three meson factories in improving the limits on these muon processes.

In the next talk Darragh Nagle will be describing the Crystal Box experiment. This is a detector that consists of a box of NaI(Tℓ) crystals that determines the energy and position of neutral and charged particle showers. It has an eight plane cylindrical drift chamber in the center for charged particle track position measurements. This experiment will be running soon and they will be simultaneously searching for the decays $\mu \rightarrow ee\bar{e}$, $\mu \rightarrow e\gamma$, and $\mu \rightarrow e\gamma\gamma$. As I said earlier, Dr. Nagle will give more details on the detector in the next talk.

The TRIUMF TPC experiment, which is currently underway, will be described by Dr. Gotow. This experiment, which is a search for the muon conversion process $\mu^- A \rightarrow e^- A$ and which has collaborators from here at VPI, uses a Time Projection Chamber (TPC) to measure the electron momentum. The muon conversion target is located at the center of the TPC. Inside the TPC there are an inner cylindrical proportional chamber and a scintillator, and outside there are scintillators and planar proportional chambers. The magnetic field setting is such that the TPC does not detect the positrons from normal muon decay that have an end-point energy of 52.8 MeV. Instead the trigger requires that a high energy particle be seen. This group is presenting new data on upper limits for muon conversion processes at the Division of Particles and Fields meeting later this week.

The SINDRUM experiment, which is now running so no one from that group could come to describe it, will start by searching for $\mu \to ee\bar{e}$. This experiment, which is shown pictorically in Fig. 3, will ultimately consist of five concentric multiwire proportional chambers inside a solenoidal magnetic field. A hodoscope outside the last wire chamber plane is used for triggering. At this time they have four working wire chamber planes and have attained 6 MeV resolution on the invarient mass, with a solid angle for the detector close to 50%. Future experiments have been considered for the detector to study π decays as well as other rare decay modes of the muon.

The LAMPF-Yale muon conversion experiment will look for muon conversions in a target inside a superconducting solenoidal magnet. The conversion electron will be detected by a TPC-like read-out plane. I have recently been told that the magnet is currently being wound and a prototype read-out plane is being tested. This experiment will not be ready for at least two years.

B. Normal Muon Decay Experiments

Table IV shows the current and anticipated errors from experiments that have been mounted to study ordinary muon decays. The results for the experiment by Dr. Strovink's group[11] have been recently published. They used a 90° spectrometer to determine the shape of the positron spectrum for positrons emitted in the backward direction with respect to the muon's polarization vector. The rate at the end-point would vanish if the decay were described by pure V-A Michel parameters. They obtained a 90% upper confidence limit $\xi P_\mu \delta/\rho > 0.9959$. If one assumes $\delta = \rho = 3/4$, the error shown in Table IV is obtained. As previously stated, it is this experiment that has been used to place the strongest model independent limits on the left-right symmetric models for the weak interaction.

The TRIUMF experiment #134/176, headed by Ken Crowe, uses a short-focusing solenoid to measure a narrow window of positron momentum. By varying the magnetic field settings they determine the momentum spectrum. The experiment was orginally designed to measure the η parameter; however, the spectrometer can be adapted to determine ξP_{μ}, in a method similar to a muon spin rotation detector by processing the μ^{+} spin around the axis of the solenoid.

Figure 4 shows the apparatus for the Los Alamos TPC muon decay experiment. The major component of the detector is a TPC. The magnetic field of the TPC is provided by an iron enclosed solenoid. Currently, the maximum obtainable magnetic field is just over 5.6 kG. This field has been carefully measured and found to be uniform to better than 0.6% within the entire TPC sensitive volume of 52 cm in length by 122 cm in diameter and this is accurate enough to make momentum measurements of the decay positrons absolutely. The TPC readout plane consists of 21 identical modules each of which has 15 sense wires and 255 pads arranged under the sense wires in rows of 17 pads each. The 21 modules are arranged so as to cover most of the 122-cm diameter area of the chamber.

The muons for the experiment are from a surface beam. These are muons derived from pions decaying at rest on the surface of the LAMPF A2 primary production target. They have a momentum of 29 MeV/c and the beam line is tuned to that momentum. The entrance to the TPC is via a 2-in. beam pipe that extends through the magnet pole parallel to the magnetic field direction. Before entering the chamber, the muons pass through a 10-mil scintillator that serves as a muon detector.[13] The scintillator is viewed, via fiber optic light guides, by two photomultiplier tubes located outside the magnet. The thresholds for the photomultipliers are adjusted to produce a coincidence for the more heavily ionizing muons and ignore the minimum ionizing beam positrons.

A deflector/separator is located in the beam line 2 m upstream of the magnet. It produces a region of crossed electric and magnetic fields through which the beam passes. This device acts firstly as a separator. This function is necessary because the beam has about 200 positrons for every muon. By the proper choice of electric and magnetic fields, a final muon to positron ratio of about 3:2 is obtained. The second function for the device is as a deflector to keep additional particles from entering the chamber once a muon is inside. This is accomplished by turning off the electric field when a muon enters the detector. Thus, by a proper choice of beam intensity, only one muon is allowed to enter the TPC at a time.

An event trigger requires that one muon enters the TPC during the LAMPF beam gate and stops in the central 10 cm of the drift region. The entering muon is detected by a coincidence from the photomultipliers attached to the 10-mil scintillator. This signal is used to operate the deflector. It also is put in delayed coincidence with a high level threshold signal from any of the central wires of the TPC within a gate whose width and delay correspond to the drift time from the central 10 cm of the TPC. If no delayed coincidence occurs, indicating that the muon did not penetrate far enough into the TPC, or a high level output is detected before the delayed gate, indicating that a muon penetrated too far, the event is rejected by the trigger. If the event is rejected, all electronics are reset and the beam is turned back on for another attempt at a muon stop after 250 μs has elapsed (to allow for complete clearing of all tracks in the TPC). The event is also rejected if a second muon enters the TPC during the 200-ns period that is required to turn off the deflector/separator electric field. If the event is accepted, the computer then reads 20-μs worth of stored data. This corresponds to the 9-μs drift time that it takes for a track to drift the full length of the TPC plus five muon decay lifetimes.

The experiment will collect about 10^8 muon decay events at a trigger rate of 120 events per second. Analysis of test data shows that for events comprising approximately 30% of all triggers, the momentum resolution $\Delta P/P$ is 0.7% averaged over the entire spectrum. Work is currently underway to improve upon the acceptance as well as the resolution. Our first full data-taking run will be late this fall.

Ultimately this experiment will be able to improve upon all four of the Michel parameters shown in Table IV, but for now the major effort will be to obtain the indicated precison on ρ. In the context of left-right symmetric theories, an improved measurement of ρ will place a new limit upon the allowed mixing angle between W_R and W_L almost independent of the mass of the W_R. Figure 6, which shows the currently allowed values for ζ and κ, including the new result from Strovink's measurement, shows what limit upon ζ will be obtained from the anticipated measurement of ρ to the precision give in Table IV.

The last experiment I will describe is the SIN positron polarization experiment. This is a measurement of the average longitudinal positron polarization, $\langle P_L \rangle$, and the two transverse polarization components, P_{T1} and P_{T2} of the positron in ordinary muon decay. The experiment will be described in more detail by Dr. Gerber, but I will just say that it detects the positron polarization by measuring the assymmetries from Bhabha scattering and positron annihilation in flight. The experiment, which has just recently been completed, has done the first measurements of the transverse polarization components and provided the data given in Tables I and IV.

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Table I. Normal muon decay parameters. The V-A predicted values as well as the current world average measured values are given.

Parameter	V-A Value	World Average
ρ	3/4	0.752 ± 0.003
η	0	-0.12 ± 0.21
ξ	1	0.972 ± 0.014
		> 0.9959[a]
δ	3/4	0.755 ± 0.008
α/A	0	0.16 ± 0.12
α'/A	0	0.14 ± 0.14
β/A	0	-0.057 ± 0.057
β'/A	0	-0.049 ± 0.057

a If the V-A values for $\delta = \rho = 3/4$ are used. The value given is a 90%-confidence lower limit.[11]

Table II. Limits on the weak interaction coupling constants. These limits were determined by the technique due to Dorenzo[4] and using the world average values for ρ, η, ξ, and δ given in Table I.

Coupling Constant	Limit
Axial Vector	$0.76 < g_A < 1.20$
Tensor	$g_T < 0.28$
Scaler	$g_S < 0.33$
Pseudoscaler	$g_P < 0.33$
Vector-Axial Vector Phase	$\phi_{VA} = 180^\circ \pm 15^\circ$

Table III. Lepton flavor violating muon processes. The table shows the upper limits established by previous experiments and the approximate sensitivity of currently running experiments or accepted proposals.

Mode	$\mu\to e\gamma$	$\mu\to ee\bar{e}$	$\mu\to e\gamma\gamma$	$\mu^-A\to e^-A$ (sulphur)	$\mu^-A(Z)\to e^+A(Z-2)$ (iodine)
World Upper Limits	$<1.7\times10^{-10}$	$<1.9\times10^{-9}$	$<8.4\times10^{-9}$	$<7\times10^{-11}$	$<3\times10^{-10}$
Crystal Box (1984) (Hoffman/Matis/Bowman) Los Alamos/ Chicago/Stanford	$<1.2\times10^{-11}$	$<7\times10^{-12}$	$<5.5\times10^{-12}$		
SINDRUM (1984) (Walter) SIN/ETH/ ZURICH/CALTECH		$\sim10^{-12}$			
LAMPF $\mu e\gamma_{II}$ (1986) (Bowman/Hofstadter) Los Alamos/ Chicago/Stanford	$\sim10^{-12}$				
TRIUMF TPC (1984) (Bryman) TRIUMF/VPI&SU/ Chicago/Victoria/ UBC/Montreal/ Carleton/NRC/ Los Alamos				$\sim10^{-12}$	
LAMPF-Yale (1986) (Hughes)				$\sim10^{-13}$	

Table IV. Experiments in progress to measure normal muon decay parameters. The table gives the errors on the current world average measurements of the Michel parameters and shows the statistical errors expected from currently running experiments. (TRIUMF #185 has been completed recently and their true error is given.)

Parameter	World Average	Los Alamos TPC (Anderson/Kinnison) Los Alamos/Chicago/ NRC	TRIUMF #134/176 (Crowe) Berkeley/UBC	TRIUMF #185 (Strovink) Berkeley/ UBC
ρ	0.0026	0.00023		
η	0.21	0.006	<0.1	
	0.066			
ξP_μ	0.012		<0.005	0.0018
δ	0.009			

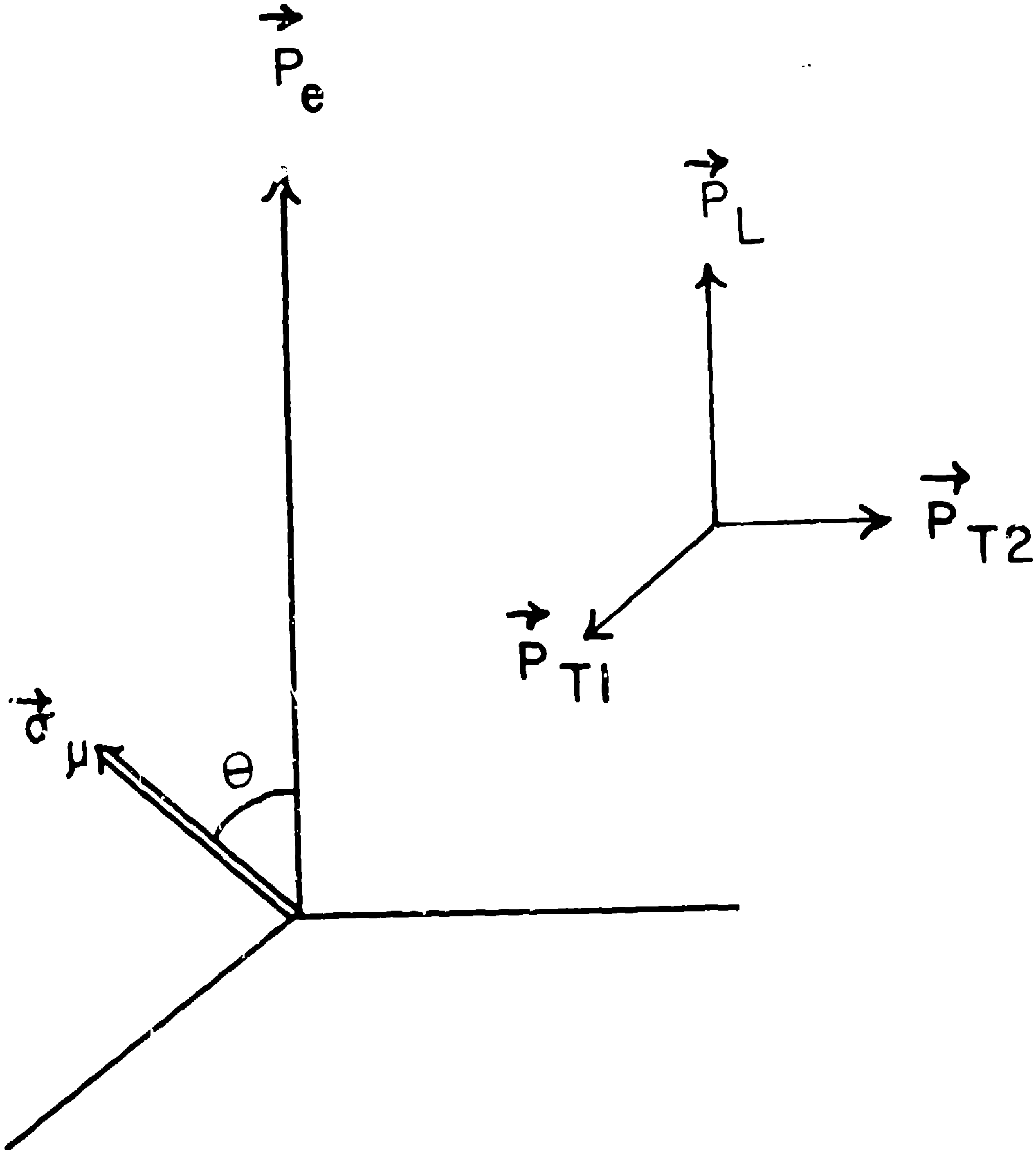
Figure Captions

1. Definition of polarization vectors. $\vec{P}_L$ is the longitudinal polarization of the electron, P_{T1} is the transverse polarization in the plane formed by the muon spin and electron polarization, and P_{T2} is perpendicular to that plane.

2. The experimental 90% confidence limits on the mixing angle, ζ, and the mass squared ratio, $\kappa=[M(W_1)/M(W_2)]^2$, characterizing right-handed currents in a possible left-right symmetric theory of electroweak interactions. The curves are based upon ξP_μ as given in Table I (dotted curve), the most recent measurement of ξP_μ of Strovink, et al.[11] (dot-dashed curve), Fermi-Teller and Fermi ξ polarizations (dashed curve--see Ref. 9), current world average value for ρ (solid curves), and the anticipated limits of ρ from the Los Alamos TPC experiment (bold solid lines).

3. A pictorial diagram of the SINDRUM apparatus showing a $\mu \to ee\bar{e}$ event.

4. A pictorial diagram of the Los Alamos TPC muon decay experiment.



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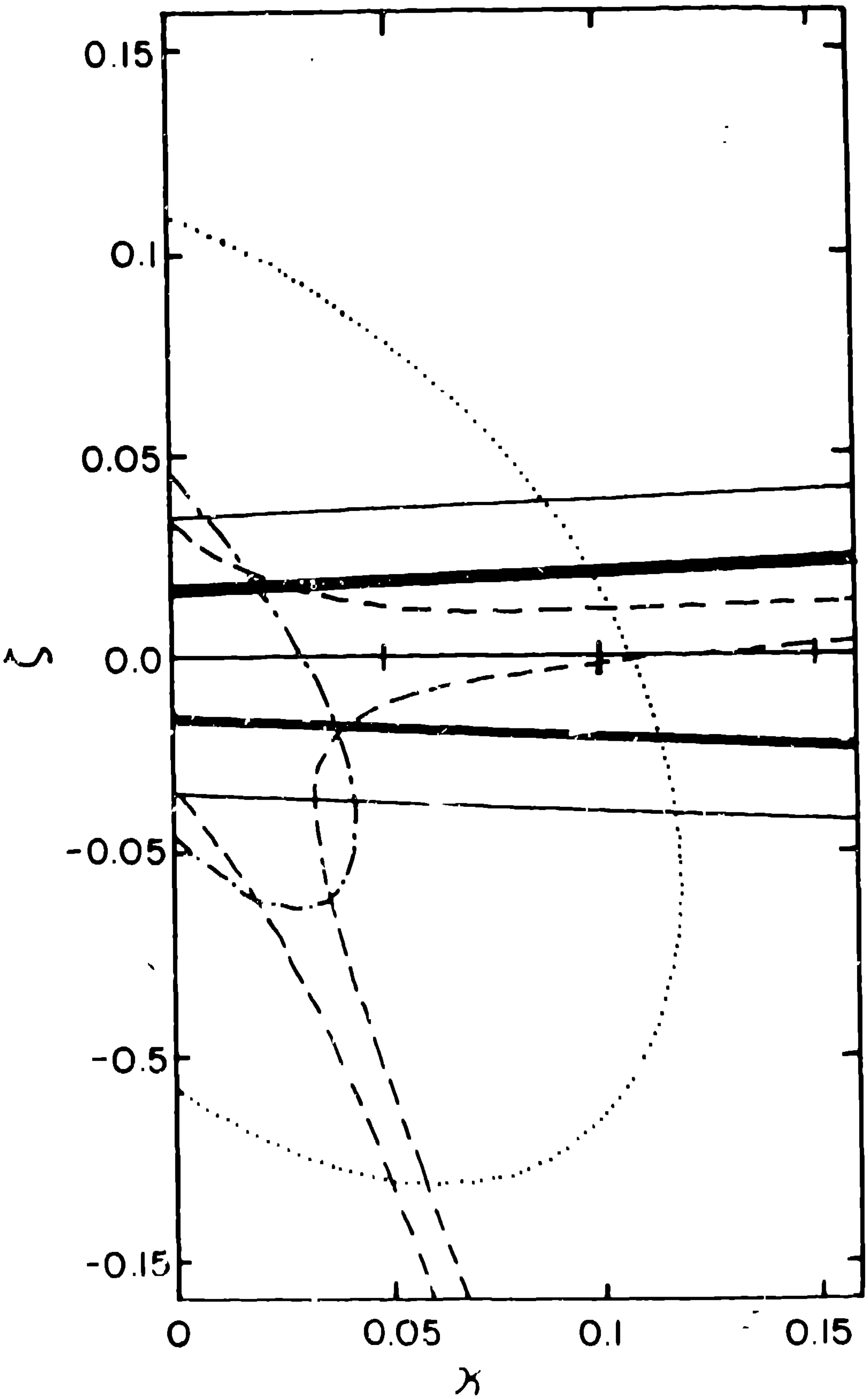

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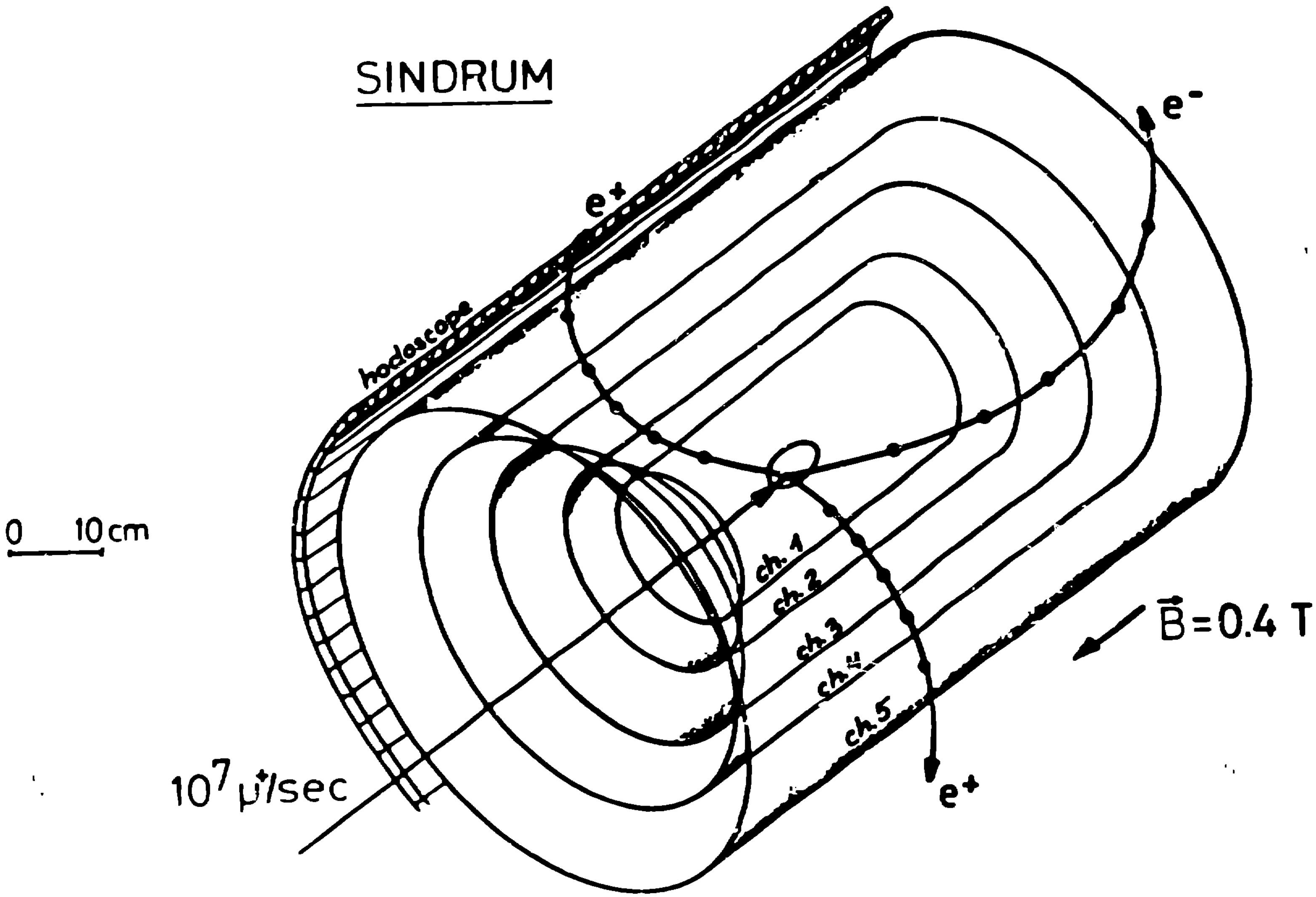
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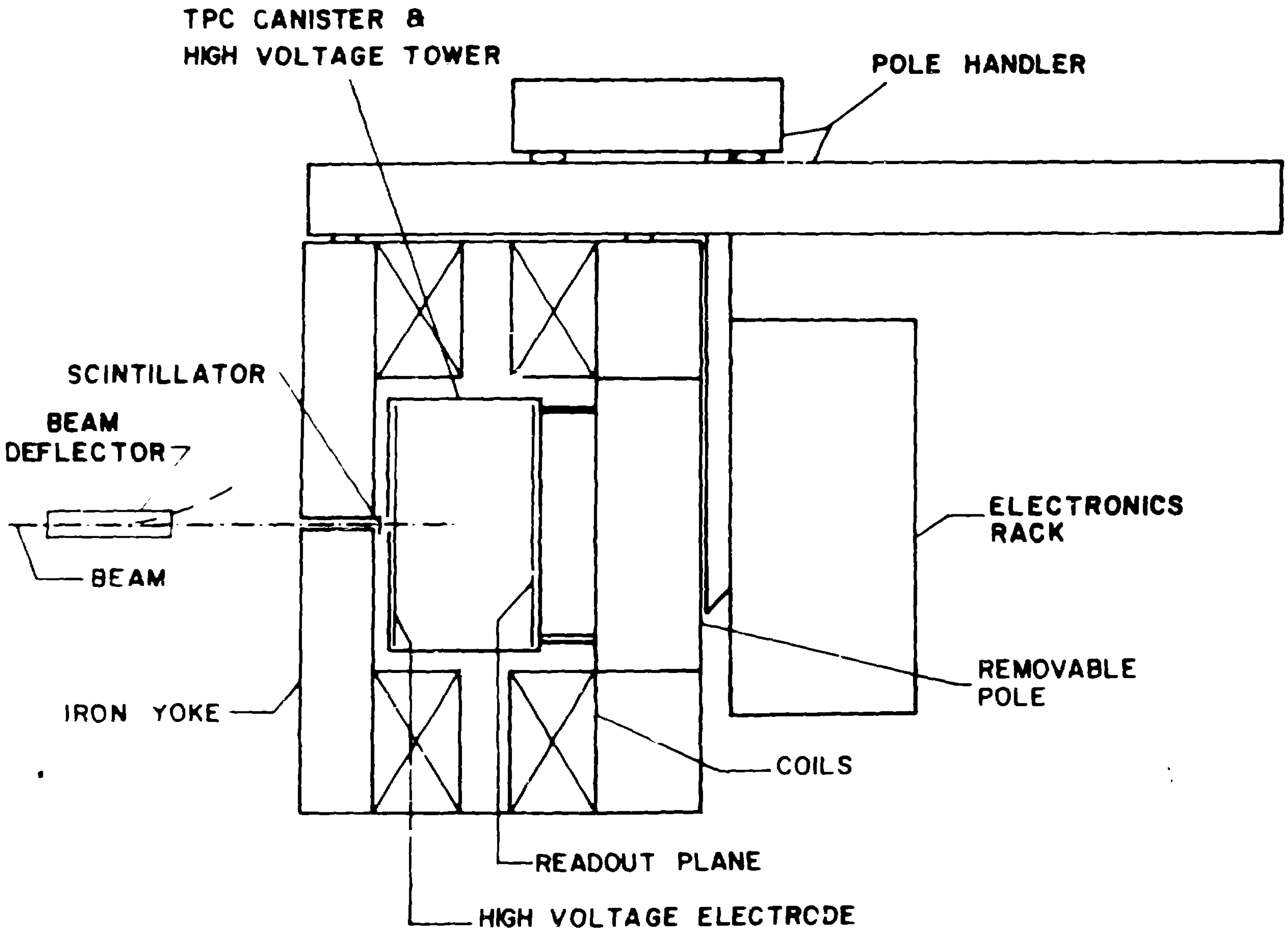
TPC CANISTER &
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COILS
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